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THE CALCULATIONS OF NUTDRIVERS ELECTRICITY CONSUMPTION WHEN ASSEMBLING FIXED THREADED JOINTS

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Abstract: *In given article the nut driver's electric power consumption studies depending on the corresponding fixed threaded joint's assembly time are made. So far there are no recommendations from the tool manufactures for nut driver's optimal operating modes (the conclusion is made based on the attached instructions which provide instrument manufacturers), when evaluating this aspect taking into account the electrical power consumption and assembly time for different types of fixed threaded joints (wood, metal, plastic, etc.) and also taking into account obtainable tightening moments.*
Keywords: fixed threaded joints, electric power, power consumption calculations, assembly time, optimization, optimal operating modes.

1. INTRODUCTION

In nowadays automated manufacturing the question concerning electric power consumption reduction is of great interest, and it leaves its impact on the final product cost. One of the options for reducing consumption of electric power is an efficient nut driver – screwdriver's use. Further is offered the example of calculations of electric motor's power consumption in order to determine the optimal operating mode when assembling fixed threaded joints.
In the literature [3, 5, 12, 13] is described the power estimation addiction from the beginning of speed and load torque, but there is no information about the energy dependence from the set speed. This is due to the fact that the electric motor is usually used at a constant or slowly changing mode. In quickly changing regime it is not possible to measure the power using the traditional methods (using a wattmeter). Using an electric motor in short-term regimes, it is needed to calculate power for each mode separately. The engine parameters are examined only in the range that they can achieve and it is not considered possibilities to extend this range. This is done because it requires additional investments in order to develope a new equipment.
Knowing what power the electric motor develops and each regime's time it is possible to determine the electric power consumption. Fixed threaded joint's assembly time consists of a rotor head's run-time, screwing time, tightening time and reaction time till the start button is released (ratchet mechanism's operating mode).
In the literature sources [8] are given the run-time and acceleration time formulas, but the impact on overall power consumption depending on this time is not viewed. This is due to the fact that the electric motor is usually operated several tenths of minutes, minutes or even hours and on the total energy consumption's background acceleration time impact is very small. By running the nut driver often with large initial set speed for a short period of time until a few seconds, the run-time energy consumption can take up to 80% of total electric power consumption throughout all operating period.

2. ASSEMBLY TIME DETERMINATION

The assembly period of thread connections, using an electric motor, depends on such parameters as acceleration of the electric motor ε, inertia of the electric motor's rotor J_{ROT}, inertia of other rotating parts of the system $J_{L,}$ rotation rate of the electric motor and other parameters.
In order to determine the assembly period, first of all it is necessary to calculate acceleration of the rotor head ε (1) at the time when the motor is being switched on till the moment when the constant set revolutions are achieved [4].

$$\varepsilon = 10^4 \cdot \frac{M_H}{J_{ROT} + J_L}. \qquad (1)$$

where: M_H – momentum developed by a motor when it is being stopped (the maximum momentum the motor can develop).
The time period t_{iesk}, when gathering rotations is done can be calculated according to the formula (2):

$$t_{iesk} = \frac{\omega}{\varepsilon}. \qquad (2)$$

where: ω – angular rate until which the rotations are gathered, s^{-1}.
In order to determine the screwing period t_{skr} (6), first of all it is necessary to determine the number of rotations n_{iesk} completed by the rotor head during the time of run-out (3) and the number of rotations needed n_{kop} to conduct assembly (5). It should be taken into account that the electric motor and rotor head have different rotation rates. The rotation ratio between the electric motor and rotor head is determined by the gear ratio A.

$$n_{iesk} = \frac{\varphi}{360 \cdot A}. \qquad (3)$$

where: φ – revolution angle done by the electric motor during the run-out period.

The revolution angle φ can be determined according to the formula (4):

$$\varphi = \frac{\varepsilon \cdot t_{iesk}^2 \cdot 90}{\pi}. \qquad (4)$$

$$n_{kop} = \frac{l}{p}. \qquad (5)$$

where: l – screwing length, mm.
p– thread pitch, mm.

$$t_{skr} = \frac{(n_{kop} - n_{iesk}) \cdot 60}{n}. \qquad (6)$$

where: n – revolutions per minute of a rotor head, min^{-1}.
The reaction period t_r values are determined experimentally. The normal value of the reaction period from the results of 10 measurements with the respective rotation ratio was used in calculations.

3. THE CALCULATIONS OF ELECTRICITY CONSUMPTION

Estimating the electric power consumption, it will be calculated in 3 stages for the time period when:
1) the motor's run-out takes place,
2) screwing with constant initial rotations takes place,
3) fastening is completed but the run button is not released yet.
The fastening period will not be taken into account provided that it is too small in comparison to the overall assembly period and has hardly any effect on the final result.
The equivalent circuit (Fig. 1) of the equipment consists of the accumulator's battery, whose electromotive force of voltage U_{BAT}, inner resistance R_{BATT} of the accumulator's battery, resistor R_E where the voltage for determination of the electric power is measured, transistor's resistance R_D, rotor coil resistance of the motor R_R and the comparator's resistance

R_{COMP}, which is equal to zero at the run time, inductance of the motor's rotor coil L, which is not taken into account in the calculations, acting in the opposite directions of the electric current flow and its value E is proportional to the motor's rotations.

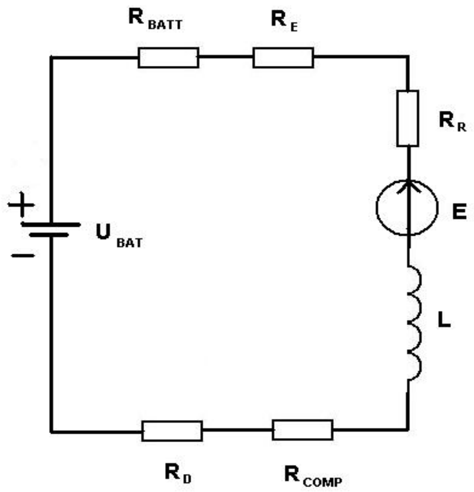

Figure 1. Equivalent circuitry of equipment

In order to calculate the energy consumption during the run-out period, first of all it is necessary to determine the current intensity. The run-out's initial current value I_{STALL} is provided in the motor's data sheet. The current intensity I_{START2} at the end of the run-out can be calculated according to the formula (7):

$$I_{START2} = \frac{U_{BAT} - E}{R_{BATT} + R_E + R_R + R_{COMP} + R_D}. \quad (7)$$

The electromotive force E is proportional to the motor's rotations n. It can be calculated according to the formula (8) [10, 12]:

$$E = \frac{n}{k_n}. \quad (8)$$

where: k_n – electric motor speed coefficient, min^{-1}/V.

Now it is possible to calculate the normal current I_{START_VID} during the run-out period. Having assumed that the current decreases linearly during the run-out period, it can be calculated according to the formula (9):

$$I_{START\_VID} = \frac{I_{STALL} + I_{START2}}{2}. \quad (9)$$

Being aware of the current value, it is possible to calculate the power P_1 developed during the run-out period according to the formula (10).

$$P_1 = U \cdot I = I_{START\_VID} \cdot (U_{BAT} - I_{START\_VID} \cdot R_{BATT}). \quad (10)$$

Every accumulator's battery has inner resistance, on which the voltage drop, that is proportional to the current, occurs. It should be taken into account when calculating the power provided that the battery's voltage can drop in half or even more with large consumable electric power that would have a large impact on the final result, not considering the correct voltage value.

Battery internal resistance R_{BAT} can be determined by the formula (11), firstly measuring battery voltage without load U_0, then it is necessary to connect the load and measure the battery voltage U_{sl} and consumed current I_{sl}.

$$R_{BAT} = \frac{U_0 - U_{sl}}{I_{sl}}. \quad (11)$$

During the screwing period with a constant rate, when the pulse-width modulator is in operation, the pulse range is equal with the I_{START2} value and it remains unchanged until the fastening period. In order to calculate the normal current value, the fill coefficient D should be known. It can be determined according to the formula (12) [1, 2, 6, 11]:

$$D = \frac{\tau}{T}. \quad (12)$$

where: τ – pulse-width, s.

T – pulse recurrence period, s.

τ and T can be determined with an Oscillograph, see Fig. 2.

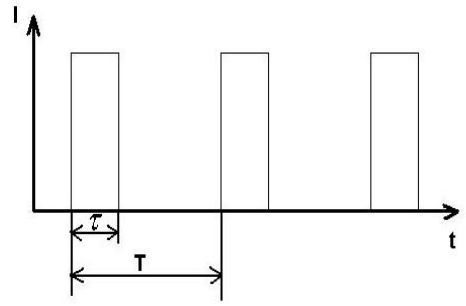

Figure 2. Impulses of the current

The normal current value I_{PULSE_AV} in the pulse mode can be calculated according to the formula (13):

$$I_{PULSE\_AV} = I_{START2} \cdot D . \qquad (13)$$

Then the power P_2 during the screwing period at a constant rate can be established according to the following formula (14):

$$P_2 = I_{PULSE\_AV} \cdot (U_{BAT} - I_{START2} \cdot R_{BATT}) . \qquad (14)$$

There are 2 cases distinguished in calculation of the electric current during the reaction period, when the nut is already fastened with the set momentum but the run button is not released yet, when:

-the electric motor is unable to develop the required momentum with the set rotations and, in order to do fastening with the set momentum, a comparator engages. This situation is characteristic to low revolutions of the rotor head (300 min^{-1}, 500 min^{-1}).

-the electric motor is able to develop the set momentum and the comparator does not engage.

In case the comparator engages, the pulse modulator stops working and the transistor is opened completely with no interruption. The electric current value in the beginning of the reaction period is equal to the I_{START2} current value, which decreases gradually. When the comparator engages, full voltage and the required electric current, which is proportional to the motor's revolutions, is delivered, but the rotor head has already stopped and the set momentum acts on the motor. The electric current decrease is justified by the fact that the electric motor starts gathering revolutions when full voltage of the battery is connected. If the electric current drops down to a certain level, the comparator would switch off and revolutions of the electric motor would decrease.

The power P_{3_COMP}, in the events when the comparator is in operation, can be calculated according to the formula (15):

$$P_{3\_COMP} = I_{START2} \cdot (U_{BAT} - I_{START2} \cdot R_{BATT}) . \qquad (15)$$

To calculate the power P_3 during the reaction period, when the comparator does not engage, first of all it is necessary to calculate the speed until which the motor's rotations n_{SL} decreased (16) [6, 10], changing the electric current value I_3.

$$n_{SL} = k_n \cdot (E - \frac{R_R M}{k_m}) . \qquad (16)$$

where: k_m – electric motor moment constant, mNm/A.

M – moment, which loads the electric motor, mNm.

The moment constant k_m is provided in the motor's data sheet. Taking into account that there are transmission gear-wheels between the motor and rotor head, the momentum M [7, 9], which works on the motor, can be calculated according to the formula (17):

$$M = \frac{M_{ROT}}{A \cdot eff} . \qquad (17)$$

where: M_{ROT} – momentum, working on the rotor head, mNm.

A – ratio between rotations of the electric motor and rotor head,

eff – efficiency of transmission gear-wheels.
Being aware of the set rotation rate until which the revolutions of the electric motor decreases, the consumable electric current value I_3 can be calculated according to the formula (18):

$$I_3 = \frac{E - \frac{n_{SL}}{k_n}}{R_{BATT} + R_E + R_R + R_{COMP} + R_D} \cdot D \,. \quad (18)$$

In the formula (18), the value E should be taken with the set rotations, when the electric motor is not loaded.
The power P_3, when the comparator is not in operation, can be determined according to the formula (19):

$$P_3 = I_3 \cdot (U_{BAT} - I_3 \cdot R_{BATT}) \,. \quad (19)$$

In order to calculate the electric power consumption during the assembly period, it is necessary to know separate parts of the assembly period, the time, when building of the electric motor's rotations t_{iesk} takes place, the time t_{skr}, when the nut is screwed with the set initial rotations and the reaction period t_r.
The time period, when fastening t_{piev} of a nut takes place is not taken into account in calculations of the electric power consumption, since it is very short and has practically no effect on the result.
The electric power E for the assembly period can be calculated according to the formula (20). The electric power E_{COMP} needed to reach the momentum, when the comparator engages, can be calculated according to the formula (21).

$$E = P_1 \cdot t_{iesk} + P_2 \cdot t_{skr} + P_3 \cdot t_r \,. \quad (20)$$

$$E_{COMP} = P_1 \cdot t_{iesk} + P_2 \cdot t_{skr} + P_{3\_COMP} \cdot t_r \,. \quad (21)$$

The graphic depiction of the obtained values using Bosch GSR 14.4 VE-2 is showed in Figure 3. and Figure 4.

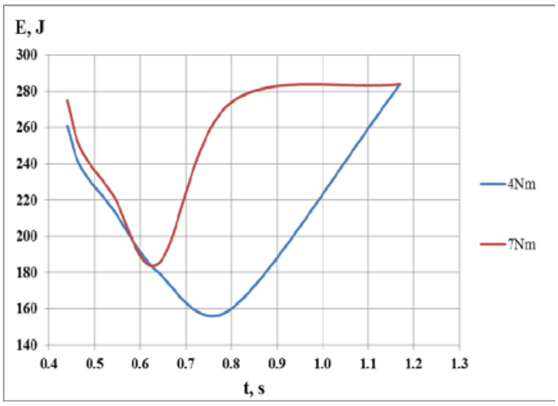

Figure 3. Theoretically determined nut driver's power consumption depending on the time of assembly and tightening torque for the bolt M6x35

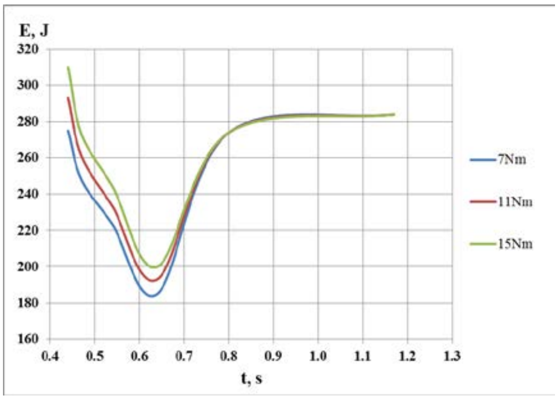

Figure 4. Theoretically determined nut driver's power consumption depending on the time of assembly and tightening torque for the bolt M8x40

4. CONCLUSIONS

The theoretical estimates of the fastening period and the consumed electric power were conducted, taking into account the rapidly changing processes of the nut driver in obtaining the rigid thread connections: run-out period, set rotations, reaction period.
It is proved that the nut driver – screwdriver has such operational modes that permit performing of the electric power optimization depending on the assembly period (using pulse-width modulator (PWM) in screwdrivers). The most economical mode of a screwdriver is at such minimum set rotations requiring no additional electric power (involving of the

comparator), providing fastening of a nut with the corresponding moment.
From the obtained graphs it is obvious that when making a fixed threaded joint at low rotational speed consumable energy does not depend on the selected torque. It is explained in such a way that when comparator is turned on, the current is close to the maximum. For the bolt M6 assembly mode is optimal at 500 min^{-1}(0, 75 s), this is due to the fact that it is possible to reach the tightening torque of 4 Nm without comparator start.
The optimal operational modes according to the electric energy consumption providing the necessary fastening moment of the fixed threaded connections, are showed in Figure 3. and Figure 4.:

1) For the bolt M6x35 at 4 Nm and 500 min^{-1} and 0,75 s of assembly time;
2) For the bolt M6x35 at 7 Nm and 700 min^{-1} and 0,63 s of assembly time;
3) For the bolt M8x40 at 7 Nm, 11 Nm, 15 Nm and 700 min^{-1} and 0, 63 s of assembly time.

Taking into account that in the computerized assembly usually using the maximum rotations of a rotor head of the nut driver (because nut drivers don't have rotation regulation options), performing optimization of the energy consumption after the assembly period, approximately from 25%-30% decreasing is obtained.
Despite the fact that simplified formulas (that are intended for electric motors with linear curves) were used for nut driver's electric consumption calculations in which were not taken into account such electric motor's parameters as inductance of rotor coils L, rotor losses (for rotors with magnetic inducement these losses are not essential), the rotor coils resistance dependence on the temperature, losses of electric power depending on frequency, they allow us to approximately determine the optimal operating mode for the nut driver if taking into account electric power consumption, assembly time and necessary tightening moments for the different types of fixed threaded joints.

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